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Original Article

FOAM FINNED DOWN FLOW TYPE AUTOMOTIVE RADIATOR RATING AND SIZING

SAKESHA[1], K. M. SUBBAIAH[2], G. L. SHEKAR[3], B. K. ANIL KUMAR[4] & ARUL ANAND[5]

[1]*P.G. Scholar, Department of Industrial & Production Engineering, NIE, Mysuru, Karnataka, India*

[2]*Professor, Department of Industrial & Production Engineering, NIE, Mysuru, Karnataka, India*

[3]*Principal & CEO, The National Institute of Engineering, Mysuru, Karnataka, India*

[4]*Lead Engineer, Mercedes-Benz Research and Development India, Bangalore, Karnataka, India*

[5]*Manager, Mercedes-Benz Research and Development India, Bangalore, Karnataka, India*

ABSTRACT

Radiator is ubiquitous cooling module of engine cooling system in automobiles. Recent advancement in engine for power forced engine cooling system is to improve its efficiency and also reduce fuel consumption along with control of engine emission to meet environmental pollution norms. It prompted investigation of alternative materials for radiators to improve its efficiency. Carbon foam was found to be one of the implementable alternative materials for fins in radiators core by considering primary factors which influence radiator performance. The most common radiator design glitches are rating and sizing. In this article, ε-NTU method is described to estimate heat transfer calculations for foam finned down flow type radiator. An application in Microsoft Excel™ is developed to assist in the calculations and analysis of radiator parameters and heat rejection for predefined size.

KEYWORDS: Down flow radiator, Carbon foam, Heat transfer, Thermal conductivity (TC)

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NOMENCLATURE

Symbols	Abbreviations		
C_w	Core width	Cp_c	Specific heat of coolant
C_L	Core length	k_c	TC of coolant
C_d	Core depth	Nu_c	Nusselt number of coolant
C_v	Core volume	f_D	Darcy friction factor
T_w	Tube width	h_c	Heat transfer coefficient of coolant
T_h	Tube Height	D_{ha}	Hydraulic diameter of air
T_d	Tube depth	A_{ra}	Free flow area of air
T_t	Tube thickness	A_a	Total heat transfer area
F_h	Fin Height	Re_a	Reynolds number for air
F_d	Fin Width	V_a	Velocity of air
F_t	Fin thickness	S_a	Kinematic viscosity of air
F_p	Fin pitch	μ_a	Dynamic viscosity of air
N_r	Number of rows for tube/fin	ρ_a	Density of air
D_{tr}	Distance between the tube rows	Pr_a	Prandtl number of air
N_{tube}	Number of Tubes	Cp_a	Specific heat of air
N_{fin}	Number of columns of Fins	k_a	TC of air
D_{hc}	Hydraulic diameter of coolant	Nu_a	Nusselt number of air
A_{it}	Inside cross-section area of tube	h_a	Heat transfer coefficient of air
A_{isat}	Total inside surface area of the tube	C_a	Heat capacity rate for air
P_{it}	Inside perimeter of tube	A_{osaf}	Total outer surface area of the fin

Re_c	Reynolds number for coolant	M_a	Mass flow rate of air
V_c	Velocity of coolant	C_c	Heat capacity rate for coolant
W_c	Volume flow rate of coolant	C_r	Heat capacity rate ratio
M_c	Mass flow rate of coolant	η_{fin}	Fin efficiency
ρ_c	Density of coolant	m_f	Coefficient for calculating efficiency of fin
μ_c	Dynamic viscosity of coolant	k_f	TC of fin material
S_c	Kinematic viscosity of coolant	F_{cl}	Corrected fin length
Pr_c	Prandtl number of coolant	η_o	Overall surface efficiency
A_b	Base surface area	$N_{fin/tube}$	Number of fins per tube
$A_{fin,\ base}$	Total fin/base surface area of a single tube	U	Overall heat transfer coefficient
R	Overall thermal resistance	NTU	Number of transfer units
A_c	Total heat transfer area of coolant	C_{min}	Minimum heat capacity
k_t	TC of tube material	C_{max}	Maximum heat capacity
η_{tube}	Tube efficiency	ε	Effectiveness
m_t	Coefficient for calculating efficiency of tube	Q_{max}	Maximum heat transfer rate
T_{cl}	Corrected tube length	Q_{pred}	Predicted heat transfer rate
A_f	Single fin surface area	T_{ic}	Inlet coolant temperature
P_f	Perimeter of fin	T_{oc}	Outlet coolant temperature
P_{tube}	Perimeter of Tube	T_{ia}	Inlet air temperature
$F\rho$	Fin density	T_{oa}	Outlet air temperature
R_A	Fin surface roughness due to the exposed pores	A_{tpb}	Total interior heat transfer surface available in interconnected pore channel
Re_d	Pore level Reynold number	Re_L	Reynolds number in fin channel
D_E	Equivalent particle diameter	Abo	Area of the front & back edges of the tube
Vf	Total volume of the fin	Nu_{sf}	Pore level average Nusselt number
ΔP	Pressure drop across the fin bank	d_v	Equivalent diameter of the void phase
C_f	Forchheimer co-efficient	f	Friction factor
C	Laminar Turbulent	K	Permeability
V_f	Total Volume of the Fin	V_{t1}	Volume of a Tube
$\varepsilon_{,}$	Relative contact size	M_{t1}	Mass of a tube
r_{cf}	Fouling factor of coolant	r_{af}	Fouling factor of air
Θ	Inclination angle for tube/fin rows		

INTRODUCTION

Designing of automotive radiator comprises various parameters which is complex with many factors involved in it. Radiator sizing and rating are the important factors which plays major role while designing radiator core. Radiator size depends on heat loading and packaging space availability in vehicle module. Heat loading depends on essential amount of heat rejection required to keep engine surface at optimum temperature. Generally Logarithmic Mean Temperature Difference (LMTD) or Effectiveness-Number of Transfer Unite (ε-NTU) method is preferred for calculation of heat transfer by the radiator. Both methods have its own advantages and preferred according to data availability. When radiator inlet and outlet temperatures of the fluids are known LMTD gives nearer solution. When any of the temperature is unknown LMTD method goes through iterations to obtain solution, in that case ε-NTU method is favored. In this article collected formulas of ε-NTU method are described to calculate heat rejection for foam finned radiator core and interpreted by excel sheet programing.

HEAT TRANSFER CALCULATIONS

Purpose of thermal analysis of radiator is to outline heat transfer surface area (sizing) and performance calculation to conclude heat transfer rate (rating). It is essential to find out amount of heat transfer and outlet temperature of the fluids from the radiator core. The ε-NTU method is based on concept of heat exchanger effectiveness [1]. Here appropriate dimensions are taken from the radiator used for heavy duty (HD) commercial vehicles. Among the two types of radiator designs (down flow and cross flow) most of the HD vehicles have down flow radiator. Based on its size heat transfer rate is calculated and validation by excel sheet programing which should fulfil the requirement.

A rectangular slotted inclined fin with grooves having uniform cross-section is attached to a flattened liner tube. It is the inclined fin-tube configuration design based on the mechanical properties of the carbon foam, the flow and heat transfer behavior, and the bond contact quality and manufacturing feasibility. Figure 1, 2, 3 and 4 shows the schematic representation of the front view of radiator core, top view of radiator core, tube layout and fin layout respective.

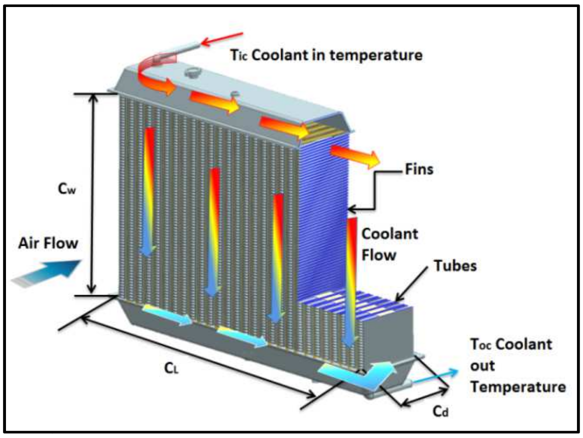


Figure 1: Foam Finned Radiator Core

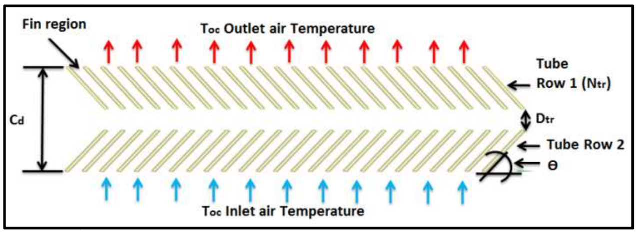


Figure 2: Schematic Top View of Radiator Core

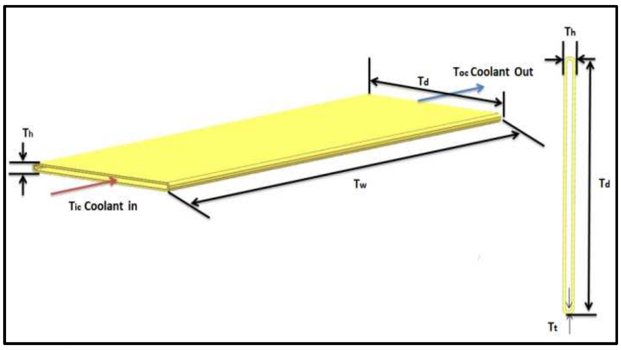


Figure 3: Tube Layout

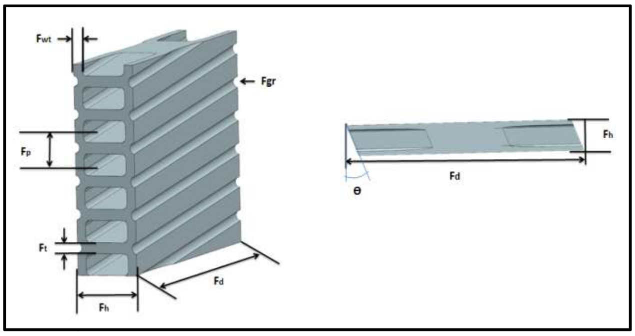


Figure 4: Foam Fin Layout

Coolant Side Heat Transfer Coefficient Calculations

Following set of equations are adopted to calculate coolant side heat transfer coefficient. Expressions are referred from 1,2,3,4 and modified.

Hydraulic Diameter:	$D_{hc} = 4*(A_{it}/P_{it})$ Where $A_{it} = (T_h*T_d)-[(T_h-T_t)*(T_d-T_t)]$ and $P_{it} = 2*[(T_h-T_t)+(T_d-T_t)]$	(1)
Reynolds Number:	$Re_c = (V_c*D_{hc})/S_c$	(2)
Prandtl Number:	$Pr_c = (\mu_c*Cp_c)/k_c$	(3)
Nusselt Number for 2300<Re<10000:	$Nu_c = [(f/8)*(Re_c-1000)*Pr_c]/\{1+[12.7*\sqrt{(f/8)}*(Pr_c^{0.6667}-1)]\}$ Where $f = 1/[1.8*\log_{10}(Re_c/6.9)]^2$	(4)
Heat Transfer Coefficient:	$h_c = (Nu_c*k_c)/D_{hc}$	(5)

Air Side Heat Transfer Coefficient Calculations

Following set of equations are adopted to calculate air side heat transfer coefficient. Expressions are referred from [1, 3, 4, 5] and modified.

Hydraulic Diameter:	$D_{ha} = 4*C_d*A_{ra}/A_a$ Where A_{ra} = [Total number of passages $*(\{2*F_t*(F_h2F_{wt})\}+\{2*F_d*(F_h2F_{wt})\}+\{2*F_{wt}*F_p\})] + [N_{tube}*(\{2*T_h*T_w*\} + \{T_d*T_w*\cos(rad(\Theta))\}] +$ [Total number of grooves$*G_a$] Total number of passages $= N_{fin}*(C_w/F_t)$ Where $N_{fin} = N_3-N_4$ N_3= Actual number of fins can accommodate $= ([(C_L-\{N_1*T_h\})/F_h]+1)*N_r$ N_4= Loosed number of fins due to inclination angle = $[(F_d*\sin(rad(\Theta))/(T_h+F_h)]$ $A_a = C_L*C_w$ and $G_a = (\pi*Gr^2)/2$ Total number of grooves= $(N_{fin}*(C_w/F_t))*2$	(6)
Reynolds Number:	$Re_a = (V_a*D_{ha})/S_a$	(7)
Prandtl Number:	$Pr_a = (\mu_a*Cp_a)/k_a$	(8)
Nusselt Number:	$Nu_a = 0.664* Re_a^{0.5}* Pr_a^{0.33}$	(9)
Heat Transfer Coefficient:	$h_a = (Nu_a *k_a)/F_d$	(10)

Heat Rejection Calculations

Following set of equations are adopted to calculate heat rejection. Expressions are referred from 1,2,4,5 and modified.

Stream Heat Capacity Rate for Air:	$C_a = M_a * Cp_a$ Where $M_a = \rho_a * A_a * V_a$	(11)
Stream Heat Capacity Rate for Coolant:	$C_c = M_c * Cp_c$	(12)
Stream Heat Capacity Rate Ratio:	C_r = (minimum of C_a or C_c)/(maximum of C_a or C_c)	(13)
Fin Efficiency:	$\eta_{fin} = \tanh(m_f * F_{cl})/(m_f * F_{cl})$ Where $m_f = [(2*h_a)/(k_f*F_t)]^{0.5}$ and $F_{cl} = F_h + (F_t/2)$	(14)
Heat Transfer Coefficient Of Fin:	$h_f= ((\sqrt{}h_a*P_f*k_f*2*F_d*F_t)*\tanh(m_f*F_h)*N_{fin/tube})$	(15)
Overall Surface Efficiency:	$\eta_o = 1-\{[(N_{fin/tube}/2)*A_f*(1-\eta_{fin})]/(A_{fin,base})\}$ Where $A_f = (2F_d*F_{cl})$ and $A_{fin,base} = ((N_{fin/tube}/2)*A_f)+A_b$ Where $A_b= (2*C_w*T_d)-(F_t*F_d*(N_{fin/tube}/2))$	(16)
Tube Efficiency:	$\eta_{tube} = \tanh(m_t*T_{cl})/(m_t*T_{cl})$ Where $m_t = [(2*h_c)/(k_t*T_h)]^{0.5}$ and $T_{cl} = T_h + (T_t/2)$	(17)
Heat Transfer Coefficient of Tube:	$h_t = ((\sqrt{}h_c*P_{it}*k_t*2*T_d*T_t)*\tanh(m_t*T_h)*N_{tube})$	(18)
Overall Heat Transfer Coefficient:	$U = (1/R_t)+h_f+h_t$	(19)
Number of Transfer Units:	$NTU_{max} = (U*A_c)$/minimum of C_a or C_c	(20)
Heat Exchanger Effectiveness:	$\varepsilon = 1-\{\exp^{([(1/Cr)*NTU0.22]*[\exp(-Cr*NTU0.78)-1])}\}$	(21)
Maximum Heat Transfer Rate:	Q_{max} = minimum of C_a or $C_c*(T_{ic}-T_{ia})$	(22)
Predicted Heat Transfer Rate:	$Q_{pred} = \varepsilon * Q_{max}$	(23)
Coolant Outlet Temperature: Air Outlet Temperature:	$T_{oc} = T_{ic}-(Q_{pred}/C_c)$ $T_{oa} = T_{ia}+(Q_{pred}/C_a)$	(24) (25)

Heat Transfer Model

Following set of equations are adopted to calculate total thermal resistance R_t. Expressions are referred from 6, 7 and modified.

Coolant Side Convection Resistance :	$R_1= (D_{hc}/(A_{isat}*k_c*Nu_c))$ Where $A_{isat}= ((2*T_d*T_w)+((2*((T_h-2*T_t)+((3.14*T_h)/2)))*T_w))$	(26)
Coolant Side Fouling Resistance :	$R_2 = (r_{cf}/A_{isat})$	(27)
Tube Conduction Resistance:	$R_3 = (T_t/(k_t*A_{isat}))$	(28)
Bond Contact Resistance:	$R_4 = T_b/(k_b*A_{tb})$ Where T_b = Bond thickness, K_b = TC of bond material, A_{tb} = Area of the bond surface. Bond contact resistance is neglected in this work.	(29)
Fin Base Conductive Resistance:	$R_5 = (H/(k_{eff}*A_a))$	(30)
Fin Base Constriction Resistance :	$R_6 = ((((\varepsilon+(1/\varepsilon))*LN((1+\varepsilon)/(1-\varepsilon)))$ $+(2*LN((1-\varepsilon^2)/(4*\varepsilon))))/(2*3.14*k_{eff}*A_a*F\rho))$ Where $\varepsilon = (F_t/(F_t+F_p))$ and $F\rho = (N_{fin/tube}/T_w)$	(31)
Fin Channel Fouling Resistance:	$R_7 = (r_{af}/A_{osaf})$ Where $A_{osaf} = (A_{fin,\ base}*N_{fin})$	(32)
Fin Channel Air Convection Resistance:	$R_8 = (F_{CL}/(\eta o*A_C*k_a*Nu_a))$	(33)
Bare Tube Fouling Resistance:	$R_9 = (r_{wf}/A_{ra})$	(34)
Bare Tube Air Convection Resistance:	$R_{10} = (T_h/(A_{bo}*k_a*Nu_a))$ Where $A_{bo} = (((2*T_h*T_w)+(T_d*T_w*((100-\Theta)/100)))*N_{tube})$	(35)
Inter Connected Pore Channel Fouling Resistance:	$R_{11} = (r_{af}/A_{osaf})$	(36)

Inter Connected Pore Channel Air Convection Resistance:	$R_{12} = (D_E/(\eta_o*A_{tpb}*K_a*Nu_{sf}))$ Where $D_E = ((6*(1-\mathcal{E}))/\beta)$ and $A_{tpb} = (V_f*\beta)$ $V_f = ((C_w*C_L*C_d*10^5)-(V_{t1}*N_{tube}))*10^{-6}$ Where $Nu_{sf} = (0.004*(d_v/D_E)^{0.35}*Re_d^{1.35}*Pr_a^{0.3333})$ $d_v = (6\mathcal{E}/\pi)^{1/3}*H$ and $Re_d = ((V_{pb}*D_E)/S_a)$ Solve $(C_f/\sqrt{K})*\rho*V_{pb}^2+(\mu/K)*V_{pb}-(\Delta P/F_d) = 0$ to get V_{pb} Where $C_f = (0.0928*(1/\mathcal{E}^{3/2}))$ and $\Delta P = (((f*(F_d/D_{ha}))+C)*(\rho_a/2)*V_a^2)$ $f = (0.11*((R_A/D_{fch})+(68/Re_L))^{0.25})$ and $K = ((36*\mathcal{E}^3)/(147*\beta^2))$ $R_A = (0.5*\sqrt{(D^2-H^2)})$ and $Re_L = ((V_a*F_{CL})/S_a)$ $C = ((0.074*Re_L^{-0.2})-(1742*Re_L^{-1}))$	(37)
Total Thermal Resistance:	$R_t = (R_{1\,2\,3}+(1/R_{9\,10}+(R_{4\,5\,6}+(1/R_{7\,8}+1/R_{11\,12})^{-1})^{-1})^{-1})$ Where Coolant side thermal resistance $R_{1\,2\,3} = (R_1+R_2+R_3)$ Main heat path thermal resistance $R_{4\,5\,6} = (R_5+R_6)$ Fin channel thermal resistance $R_{7\,8} = (R_7+R_8)$ Major resistance for bare tube $R_{9\,10} = (R_9+R_{10})$ Inter connected pore channel thermal resistance $R_{11\,12} = (R_{11}+R_{12})$	(38)

Total Weight of the Core Calculations

Total Mass of The Tubes:	$M_T = (M_{t1}*N_{tube})/1000$ Where $M_{t1} = (\rho_t*V_{t1})$	(39)
Total Mass of The Fin:	$M_F= (\rho_f*V_f)/1000$	(40)
Total Weight:	$W_T = (M_T+M_F)/1000$	(41)

ANALYTICAL APPROACH

The parameters considered for analytical approach are recorded in Table 1. Materials considered for radiator core are aluminium 7072 for the tubes and Carbon foam POCO™ for the fins. Properties of coolant and air for the theoretical calculations are from 8. Table 2 gives summary of properties for the fin material Carbon foam POCO™ specimen tested by Straatman9.

Table 1: Inputs for Theoretical Calculations

Description	Parameter		Value	Unit
Core	Core width	C_w	0.896	m
	Core length	C_L	0.982	m
	Core depth	C_d	0.055	m
	Angle of tube inclination	Ө	25	°
	Number of rows for tube/fin	N_r	1	In numbers
	Distance between the tube rows	D_{tr}	0	m
Tube	Tube width	T_w	0.896	m
	Tube Height	T_h	0.0028	m
	Tube depth	T_d	0.0607	m
	Tube thickness	T_t	0.0007	m
	TC of tube material(Aluminium 7072)	k_t	227	W/mK
	Density of Tube material	ρ_t	2.62	g/cm^3
Fin	Fin Height	F_h	0.007	m
	Fin Width	F_d	0.0607	m
	Fin thickness	F_t	0.001	m
	Fin pitch	F_p	0.002	m
	Fin wall thickness	F_{wt}	0.001	m
	Grove radius	G_r	0.0005	m
	TC of fin material Carbon foam POCO™	k_f	1700	W/mK
	Density of fin material	ρ_f	0.6	g/cm^3
Coolant	Inlet coolant temperature	T_{ic}	384.15	K

	Mass flow rate of coolant	M_c	6.1	Kg/s
Air	Inlet air temperature	T_{ia}	314.15	K
	Velocity of air	V_a	4.1	m/s

Table 2: Summary of Properties for the Fin Material Carbon Foam POCO™ Specimen Tested By Straatman9

Parameter	Values	Unit
Porosity Ɛ	82	%
Internal area factor β	5240	m^2/m^3
Effective conductivity k_{eff}	120	W/mK
Average void diameter D	0.0005	m
Dimension of unit cube H	0.00041	m

VISUAL BASICS FOR APPLICATION

A computer program in Microsoft Excel™ visual basics for application is implemented to develop an application to assist in the calculations and analysis of radiator parameters and heat rejection for predefined size**.** Few input parameters will give exact idea regarding heat rejection. Application will help to estimate impact on heat rejection rate of the radiator by varying tube and fin dimensions, TC of the materials, coolant and air flow rate etc.

Output Page

In output page shown in figure 5, maximum heat transfer (Qmax) and predicted heat transfer (Qpred) are programmed to display. Output temperatures of the fluids are programed in the same page. Number of tubes and number of columns of fins which can fit in core size defined by core data page is mentioned. Furthermore mass of the core is programed according to material selected for tube and fins in the tube and fin data page.

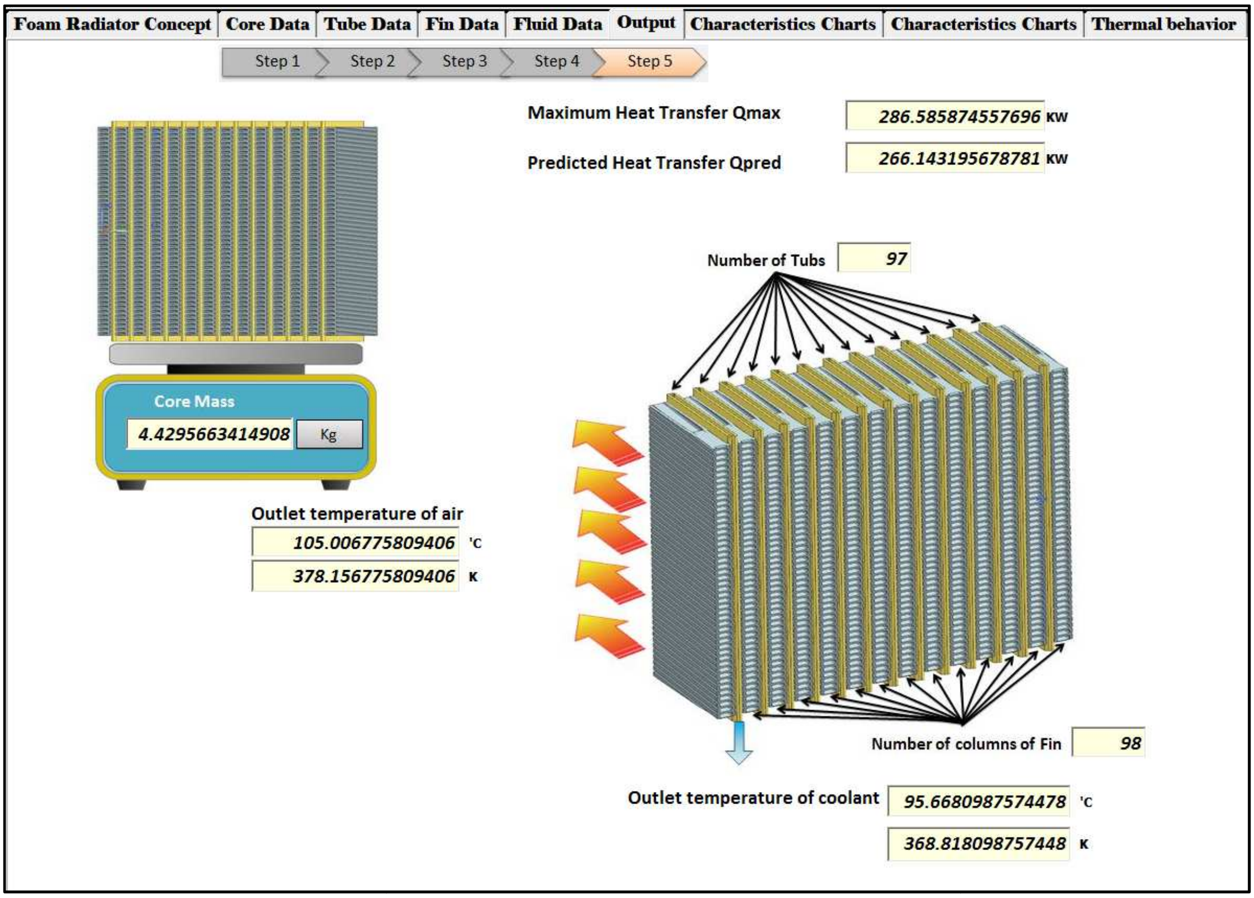


Figure 5: Image of Output Page of Developed Application in Visual Basics of Microsoft Excel™ for Down Flow Radiator Sizing and Rating

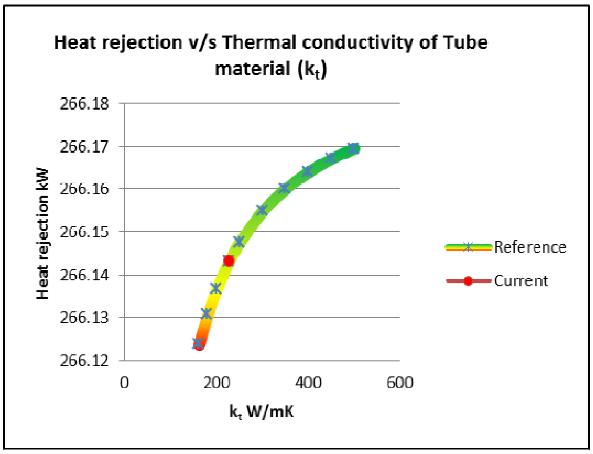
RESULTS AND DISCUSSIONS

Results obtained from analytical method are compared with the application for predefined values of table 1. Heat transfer rate by the radiator with coolant and air outlet temperature are listed and compared in table 3.

Table 3: Comparison of Analytical and Application Results

Parameter	Analytical Results	Application Results	Unit
Maximum heat transfer Q_{max}	286.58	286.5858	KW
Predicted heat transfer Q_{pred}	266.14	266.1413	KW
Coolant outlet temperature T_{oc}	368.81	368.81809	K
Air outlet temperature T_{oa}	378.15	378.15677	K
Core mass	4.4	4.4295	Kg

Comparison shows that both results closely matched with each other. Thus theoretical thermal analysis of radiator using ε-NTU method is interpreted by excel sheet program. From developed application, heat rejection verses different values of TC of the tube and fin material is plotted and shown in figure 6 and 7 respectively.



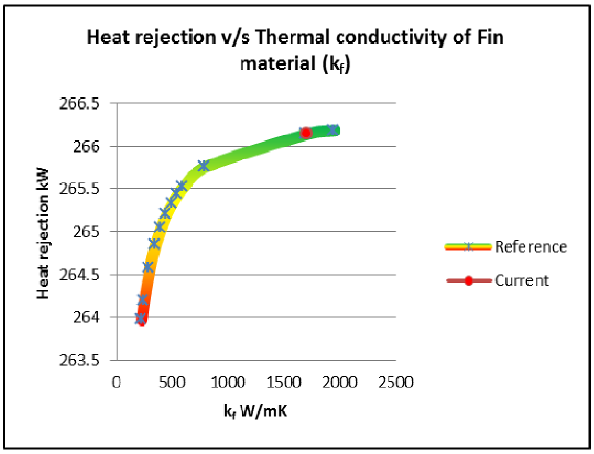


Figure 6: Heat Rejection V/S TC of Tube Material K_t **Figure 7: Heat Rejection V/S TC of Fin Material K_f**

CONCLUSIONS AND DISCUSSION FOR FUTURE WORK

The heat transfer of down flow radiator is justified analytically by collected formulas of ε-NTU method. There were numerous assumptions minimized that were essential to complete the theoretical calculations which can meet practical condition. This simplified approach to foam finned down flow radiator rating and sizing, accounts for the change in heat transfer due to variation in ambient (inlet) temperature of air with respect to the different values of TC of the fin and tube materials. The comparison between lower TC and better TC from the characteristic chart shows that more heat is lost in radiator when using better thermal conductive material.

This work can be extended to do CFD analysis of the rated foam finned down flow radiator model from the application and conclude heat transfer rate for higher thermal conductive material. However actual practical conditions are different, and how this affects the results for efficient cooling performance needs to be determined. It was further concluded by this work that thermal properties of radiator core material are influenced by the mean ambient air and coolant temperature. It will be interesting to see implementation of application developed to meet practical conditions based on the method adopted in this work.

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REFERENCES

1. *S. Kakac, H. Liu (1998). Heat Exchangers Selection Rating and Thermal Design, CRC Press LLC.*
2. *M. Carl, D. Guy, B. Leyendecker, A. Miller, and X. Fan,(2012). The Theoretical and Experimental Investigation of the Heat Transfer Process of an Automobile Radiator, Proc. ASEE Gulf Southwest Annual Conference, El Paso, Texas, 1-12.*
3. *R. Esmaeili Sany, M. H. Saidi, J. Neyestani, (2010). Experimental Prediction of Nusselt Number and Coolant Heat Transfer Coefficient in Compact Heat Exchanger Performed with ε-NTU Method, The Journal of Engine Research, Vol.18, 62-70.*
4. *K.Y. Leong, R. Saidur, S.N. Kazi, A.H. Mamun, (2010). Performance investigation of an automotive car radiator operated with nano-fluid-based coolants (nano-fluid as a coolant in a radiator), Applied Thermal Engineering, 30(17-18), 2685-2692.*

5. *D. G. Charyulu, G. Singh, J.K. Sharma, (1999). Performance evaluation of a radiator in a diesel engine- a case study, Applied Thermal Engineering 19(6), 625-639.*
6. *Qijun Yu, Anthony G. Straatman, Brian E. Thompson, (2006). Carbon-foam finned tubes in air–water heat exchangers, Applied Thermal Engineering 26, 131–143.*
7. *C.P. Kothandaraman, S. Subramanyan (2013). Heat and mass transfer data book (seventh edition). New Age International Publishers.*
8. *Keenan, Chao, Keyes, Gas Tables, Wiley, (1984). Thermophysical Properties of Matter. Vol. 3: Thermal Conductivity, Y. S. Touloukian, P. E. Liley, S. C. Saxena, Vol. 11: Viscosity, Y. S. Touloukian, S. C. Saxena, and P. Hestermans, IFI/Plenun, NY, 1970, ISBN 0-306067020-8: Ethylene Glycol product guide MEGlobal.*
9. *Straatman, A. G., Gallego, N. C., Yu, Q., and Thompson, B. E. (2006). "Characterization of Porous Carbon Foam as a Material for Compact Recuperators," Proceedings of ASME Turbo Expo 2006, Paper No. GT2006–50958, Barcelona, Spain.*